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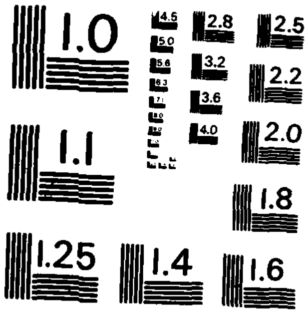

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TECHNICAL REPORT NO. 2

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G. C. Bjorklund, W. Lenth, and C. Ortiz

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Cryogenic frequency domain optical mass memory

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Abstract

Cryogenic frequency domain optical memories based upon photochemical hole burning offer the possibility of storing data at densities of up to 10^{11} bits/cm^2. The basic principles of photochemical hole burning are reviewed. Recent results on recording materials, data reading and writing, and configurations are presented.

Introduction

The spatial storage density of conventional optical memories is limited by diffraction to a maximum of 10^8 bits/cm^2 for planar geometries. The phenomenon of photochemical hole burning allows optical frequency to be utilized as an additional dimension for the organization of an optical memory.[1] Up to 10^3 bits of information can be recorded at each spatial storage location and spatial storage densities of $10^3 \times 10^8$ bits/cm^2 or 10^{11} bits/cm^2 are ultimately possible.

In this paper we review the basic principles of photochemical hole burning and present new results on recording materials, data reading and writing by FM spectroscopy, and memory configurations.

Photochemical hole burning

Certain low temperature solid state materials such as aggregate color centers or molecules in solution have spectra which exhibit relatively sharp inhomogeneously broadened absorption lines with widths $\Delta\omega_I$ varying from several cm^{-1} in crystalline solids to over 100 cm^{-1} in glasses and polymers. As shown in Figure 1, such inhomogeneous line is the result of the superposition of many much narrower homogeneous lines of width $\Delta\omega_H$ whose center frequencies are shifted by the random local environments in the crystal. The value of $\Delta\omega_H$ is determined by intrinsic molecular relaxation processes and at 2K can be as narrow as 0.00067 cm^{-1} (20 MHz) in crystals and 0.1 cm^{-1} in glasses. Thus, $\Delta\omega_H$ is typically 10^3-10^4 times narrower than $\Delta\omega_I$.

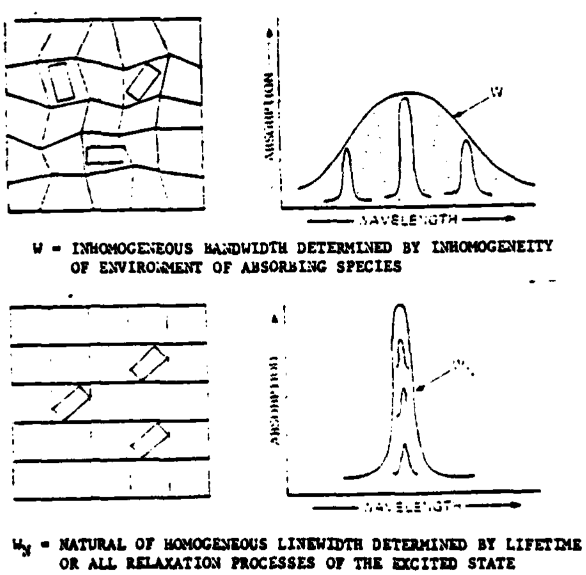


Figure 1. Homogeneous and inhomogeneous linewidths for molecules in solid state solutions.

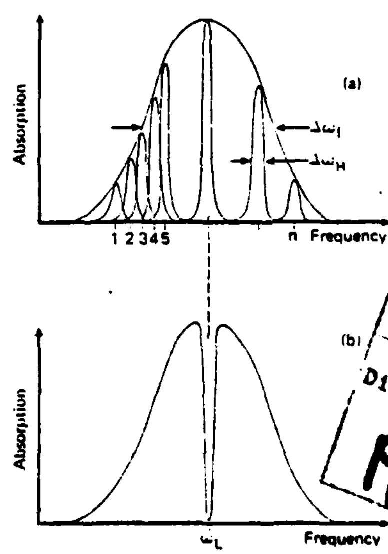


Figure 2. (a) Inhomogeneous lineshape before laser irradiation. (b) Inhomogeneous lineshape after irradiation with laser at frequency ω_L.

The phenomenon of photochemical hole burning (PHB) occurs when a permanent photochemical process is induced by a laser beam tuned to a particular frequency within the inhomogeneous line. The laser radiation interacts only with that subset of molecules, whose local environments are such that the laser wavelength is contained within their homogeneous absorption lines (see Figure 2). Since the photochemistry depletes the population of this subset, the absorption coefficient at the exact laser wavelength ω_L is reduced. In this way, a permanent "hole" or dip is produced in the inhomogeneous line profile. For shallow holes, the hole width is equal to twice $\Delta\omega_H$. Thus, 10^3 resolvable holes can be burned in a given inhomogeneous line. As shown in Figure 3a, 10^3 bits of information could be recorded at each spatial storage location by the presence or absence of holes at specific frequency locations within the inhomogeneous line.

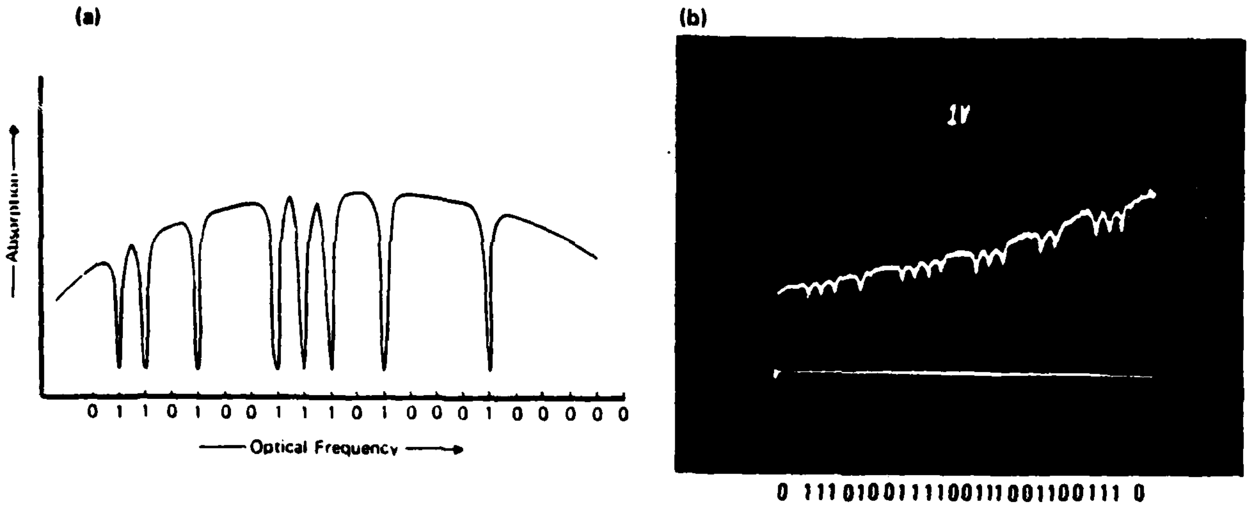


Figure 3. (a) Illustration of information storage by photochemical hole burning. Bits of information are encoded by the presence or absence of photochemical holes at various frequency locations of an inhomogeneously broadened absorption line. (b) Sequence of 150 MHz wide photochemical holes burned into a 15 GHz wide portion of the 5746Å zero-phonon line of an aggregate color center in NaF.

At present, the most promising materials for optical memories based upon PHB are the aggregate color centers in alkali halide crystal hosts.[2,3] Figure 3b shows a string of binary information recorded by 150 MHz wide holes burned into a portion of the 5749Å zero-phonon line of an aggregate color center in NaF. These holes can be erased by illuminating the sample with incoherent UV radiation of 4000Å or shorter. Figure 4 shows proposed mechanisms for the writing and erasing processes. Both mechanisms are based upon electron tunneling from excited states.

In addition to possessing good hole-burning properties, these materials meet the practical requirements of stability at room temperature, good optical quality, reversibility, potential compatability with GaAlAs lasers (see Figure 5), and capability of being produced in thin films.[3] This thin film capability is important, in order to achieve storage densities of 10^{11} bits/cm^2, it is necessary to utilize tightly focused laser beams with limited depth of focus.

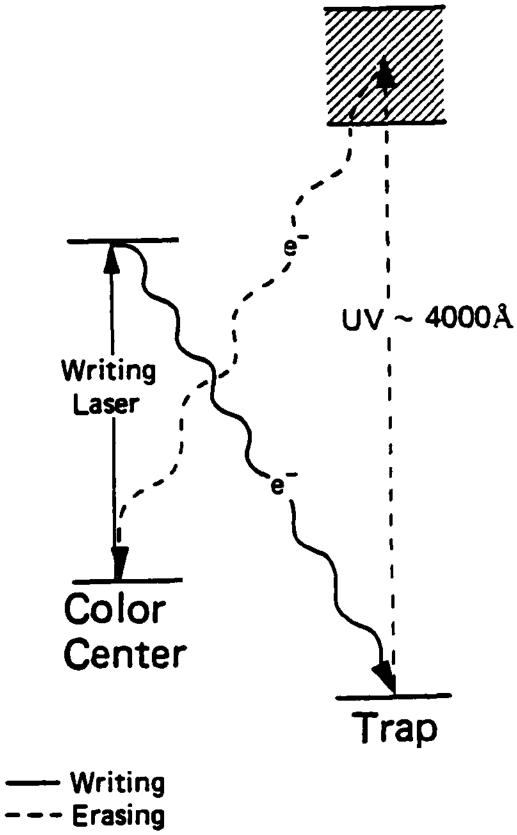


Figure 4. Color center hole burning (writing) and erasing mechanisms.

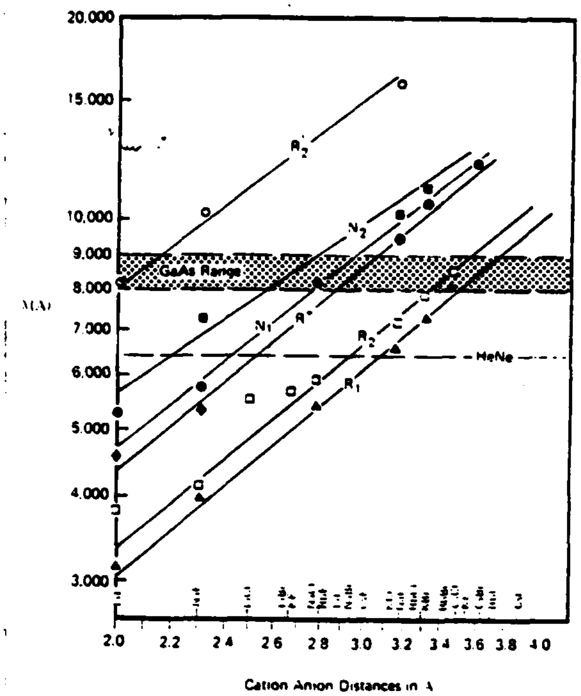


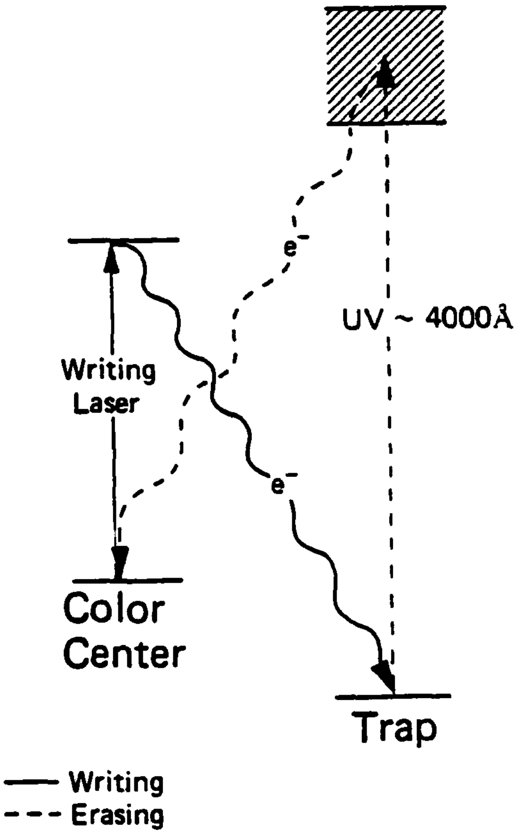
Figure 5. A Mollwo-Ivey plot of λ_{max} for several types of aggregate color centers in alkali halide hosts. The associated zero-phonon lines are usually no more than a few hundred Å to the red of λ_{max}.

Data reading and writing using FM spectroscopy

In order to effectively utilize the very large storage capabilities which PHB memories offer, it is necessary to develop means for rapidly writing data into and reading data out of the memory. Both the writing and reading speeds are limited by the time delay in accessing the desired spatial location and by the time delay encountered in tuning the laser to the desired optical frequency. In addition, the writing speed is limited by the intrinsic rate of the hole burning photochemistry, while the reading speed is limited by the dwell time necessary to detect the presence or absence of a hole with sufficient signal to noise.

The newly developed technique of frequency modulation (FM) spectroscopy[4-6] allows rapid laser frequency tuning and rapid detection of the holes. This technique utilizes widely spaced optical FM sidebands to read or write the holes. The FM optical spectrum is produced by passing the output of a single frequency laser oscillating at optical frequency ν_c through a phase modulator driven at radio frequency ν_m to produce a carrier at ν_c and two sidebands of $\nu_c \pm \nu_m$. Up to 200 GHz of optical frequency can be accessed by tuning ν_m with ν_c fixed.

Figure 6 shows a typical experimental arrangement for detecting a hole by FM spectroscopy. The FM light is incident on a sample containing a narrow spectral feature (the hole). The values of ν_c and ν_m are such that the spectral feature is probed by a single isolated sideband. The sidebands thus experience different amounts of absorption in traversing the sample. This distortion of the FM spectrum results in a heterodyne beat signal at the rf modulation frequency ν_m that is picked up by the fast photodetector which monitors the emerging beam. The strength of the absorption or dispersion associated with the hole is determined by measuring the phase and strength of the beat signal. The advantages of FM spectroscopy for reading are that there is no signal unless the sidebands are unbalanced, the narrow linewidth of the original laser source is preserved, the hole is exposed to very low power densities, and the sensitivity can be shot noise limited.



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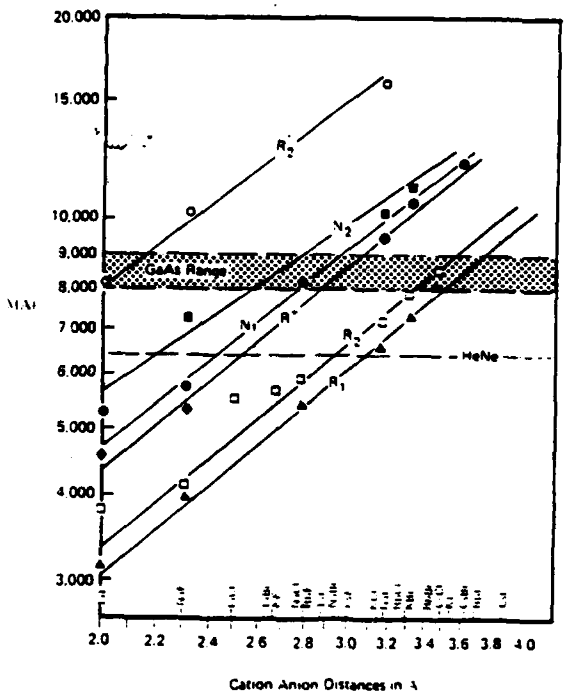

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Figure 7 indicates a somewhat different arrangement. Here, the value of ν_m is held constant at a value near 100 MHz and ν_c is varied by tuning the laser. The sideband spacing is now less than the width of the hole and the resulting FM spectroscopy signal gives the derivative of the hole lineshape. Figure 8 shows a typical experimental FM spectroscopy signal characteristic of a single photochemical hole and Figure 9 shows data proving that photochemical holes can be detected in microseconds using this method.

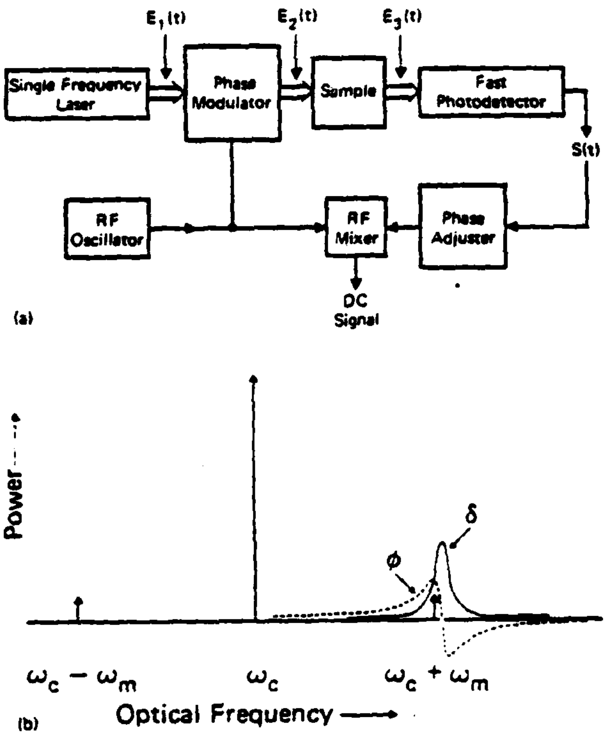

Figure 6. (a) A typical experimental arrangement for FM spectroscopy. (b) Frequency domain illustration of FM spectroscopy.

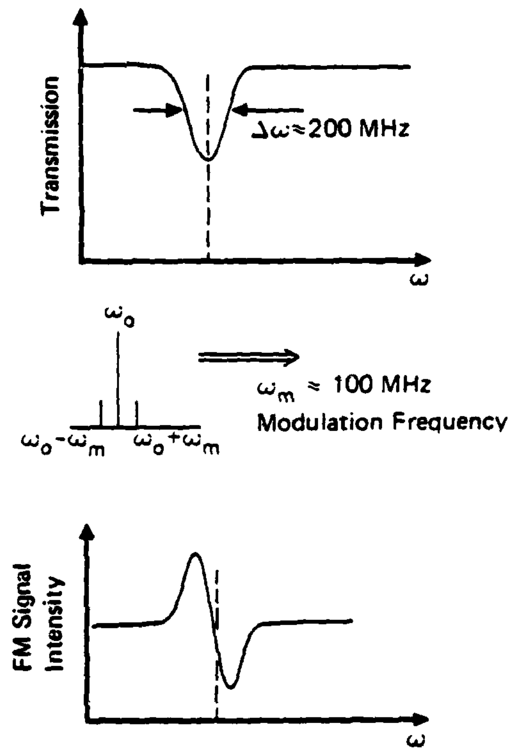

Figure 7. Frequency domain illustration of derivative FM spectroscopy.

The fastest reading and writing speeds could be achieved using a multiplex version of FM spectroscopy. The carrier frequency ν_c would be supplied by a fixed frequency laser operating at an optical frequency near to, but not coincident with, the inhomogeneous absorption band. The phase modulator would be driven simultaneously at n different RF frequencies, $\omega_1, \omega_2, \ldots, \omega_K$ and n pairs of upper and lower FM sidebands would be produced at frequencies $\omega_c \pm \omega_1, \omega_c \pm \omega_2, \ldots, \omega_c \pm \omega_K$. Thus, as shown in Figure 10, each sideband would probe a separate optical frequency location.

Reading would be accomplished by producing weak sidebands at all possible hole locations and monitoring the light emerging from the sample. The presence or absence of a hole at a given optical frequency would be determined by monitoring the intensity of the corresponding RF beat signal. If 1000 sidebands spaced by 100 MHz were utilized, complete reading of all of the information encoded at a specific spatial storage location could theoretically be accomplished in less than 100 nsec, resulting in burst reading data rates of 10^{10} bits/sec.

Writing would be accomplished by driving the phase modulator with intense RF fields at selected frequencies. This would produce strong simultaneous FM sidebands at the frequency locations where hole burning would be desired. Only the upper FM sidebands would burn holes, since the carrier and lower sidebands would not be within the inhomogeneous absorption bands.

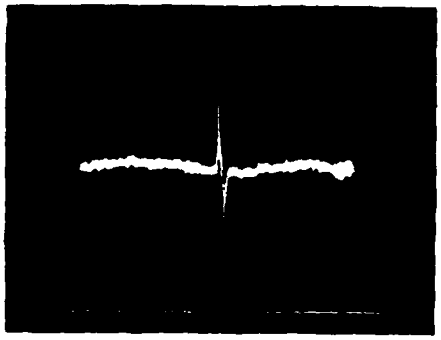

Figure 8. Experimental FM spectroscopy signal characteristic of a single photochemical hole.

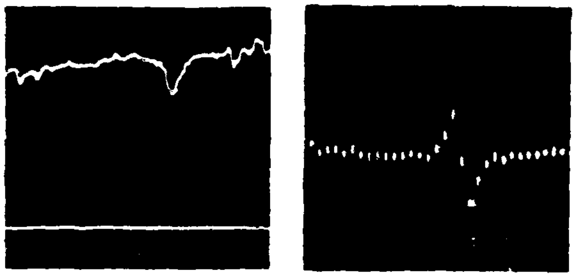

Figure 9. Experimental demonstration of fast detection of a photochemical hole using FM spectroscopy. The figure on the left shows a photochemical hole detected using standard excitation spectroscopy and signal averaging. The figure on the right shows the FM spectroscopy signal arising when the laser beam was chopped to form a train of widely separated μsec duration pulses.

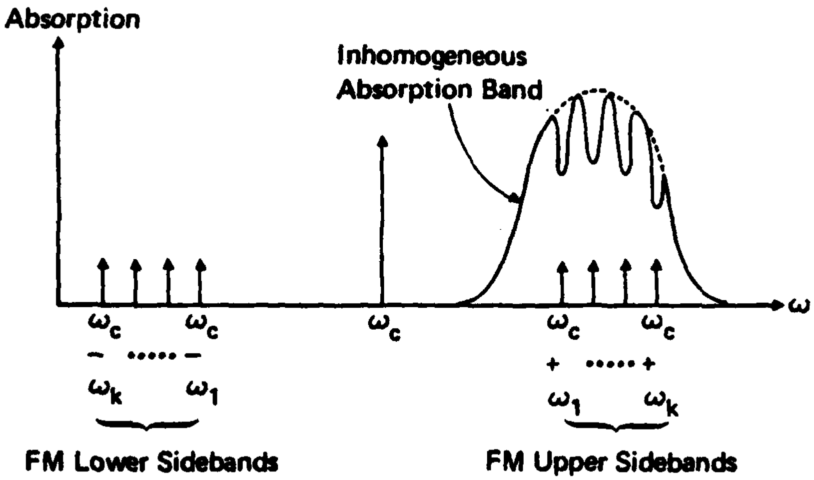

Figure 10. Frequency domain illustration of multiplex FM spectroscopy.

PHB memory configurations

The derivative FM spectroscopy approach illustrated in Figures 7, 8 and 9 provides the basis for a memory configuration which is equivalent to a very large direct access storage device (DASD) system. In today's technology, DASD devices are based on inductive magnetic recording on disks.

Figure 11 shows the reading and writing timing diagram for this configuration. The laser frequency is repetitively ramped between ω_{min} and ω_{max} at a 30 kHz rate. This type of scanning can easily be achieved with current tuned GaAlAs lasers. Thus every 30 µsec, the laser is scanned over the inhomogeneous line. For writing, the effective photochemical hole burning rate is controlled by a time varying external gating voltage. This gating could be achieved, for instance, by driving a fast light gate placed in front of the recording medium or by using an external field to control the quantum yield of the hole burning process itself. For reading, the laser is FM modulated at ω_m less than or equal to the hole width and the raw derivative FM signal monitored as a function of time. The differentiation process effectively suppresses the slowly varying inhomogeneous lineshape. Pulse shaping electronics are employed to reproduce the original data pulse shapes.

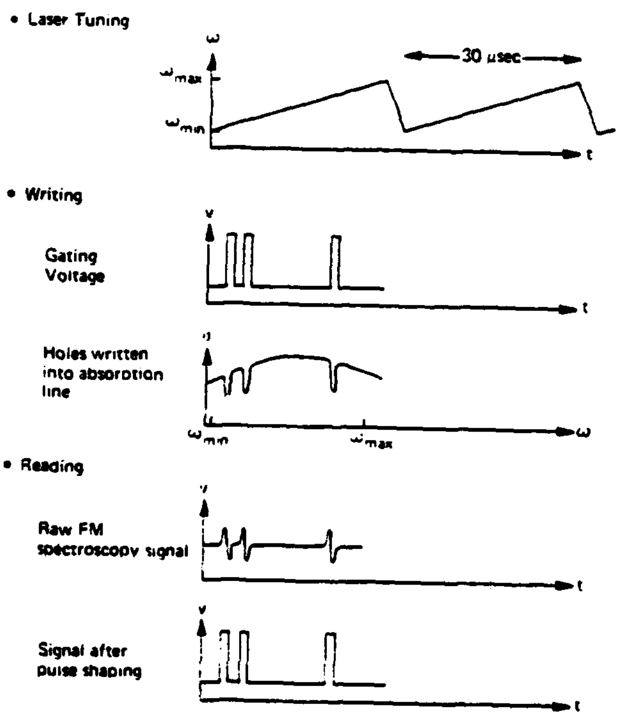

Figure 11. Reading and writing timing diagram for DASD-type configuration.

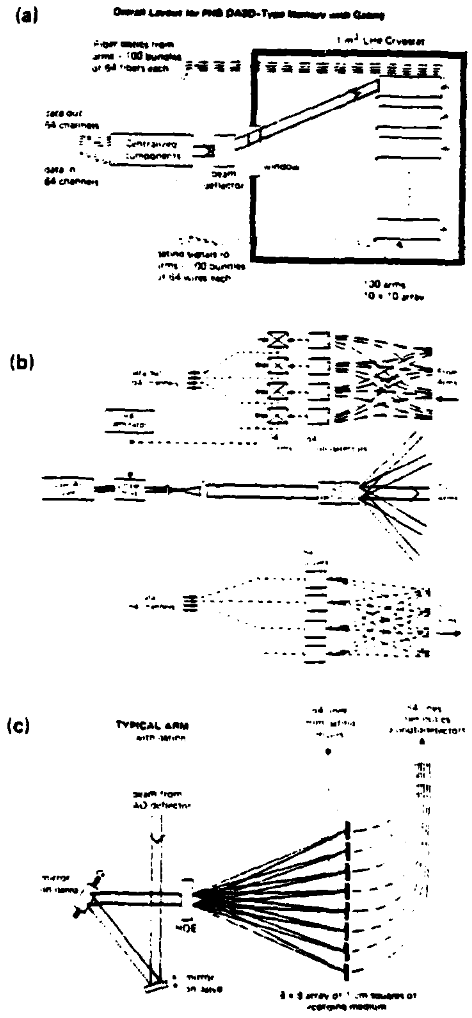

Figure 12. (a) General layout for DASD-type configuration with 100 arms. (b) Centralized components. (c) A typical arm.

Figure 11 shows a multiple arm memory system constructed using these principles. The centralized components consist of the current tuned GaAlAs laser, the phase modulator and driver, an array of 64 photodetectors followed by double balanced mixers, an array of 64 gating drivers, and a 100 spot acousto-optic deflector for arm selection. Each arm consists of a $10^3 \times 10^3$ spot XY galvonometer driven mirror pair, a holographic optical element which acts both as a focusing lens and 64× beam multiplexer, and an array of 64 1-cm squares of recording medium. The 100 arms are contained in a 1 m^3 LHe cryostat.

Each 1-cm square of recording medium contains 10^6 spatial storage locations and hence $10^3 \times 10^6$ or 10^9 bits of information. Each arm thus contains 6.4×10^{10} bits and the entire system contains 6.4×10^{12} bits. The data is organized into 6.4×10^4 bit pages, each defined to consist of 10^3 time domain bits flowing in the 64 parallel data channels. The time to read or write a page is thus 30 μsec.

Since galvonometer driven mirrors have settle times on the order of 3 msec, only 1% of the time for each arm is spent reading or writing data. The remaining 99% of the time is effectively dead time while the mirrors are moving to the next position. This makes possible time sharing of the centralized components among the 100 arms to insure that data is being read or written into one of the arms at all times. Thus the average data rate is on the order of 2×10^9 bits/sec. Data erasing is most easily accomplished on an arm-by-arm basis using flood illumination from a UV lamp.

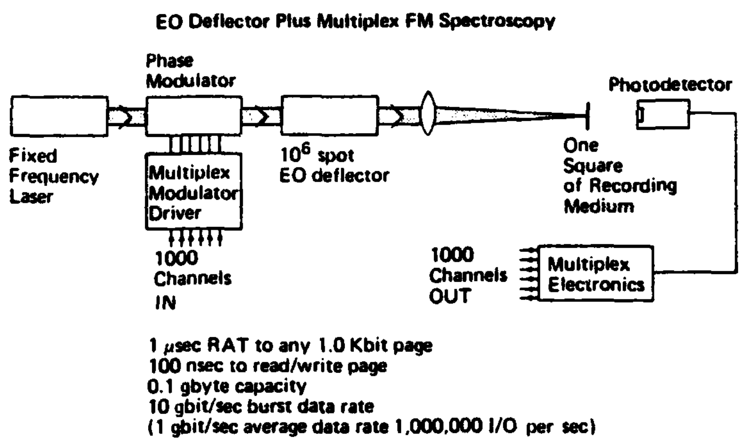

Figure 13. Memory configuration using multiplex FM spectroscopy and electro-optic beam deflection.

The multiplex FM spectroscopy approach illustrated in Figure 9 coupled with electro-optic beam deflection provides the basis for an unusual memory configuration with extremely high data rates and fast random access times, but with limited total storage capacity. Figure 13 shows the overall setup. The output of the fixed frequency laser is passed through the phase modulator driven simultaneously at 1000 different RF frequencies. For writing, the intensity of each of the RF fields is directly controlled by the corresponding input data channel. The laser beam is next passed through a 10^6 spot electro-optic deflector with 1 μsec random access time to each spot and focused onto a 1-cm square of recording medium. Reading is accomplished by utilizing phase-sensitive multiplex electronics to analyze the photodetector output and drive the 1000 parallel data output channels.

The total memory capacity would be $10^3 \times 10^6$ or 10^9 bits of information. The data is organized into 1000 bit pages, each defined to consist of 1 time domain bit flowing in 1000 parallel data channels. The time to read or write a page is 100 nsec, corresponding to a burst data rate of 10^{10} bits/sec. The average data rate is limited by the random access time to 10^9 bits/sec.

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